A Signal-Processing Framework for Inverse Rendering

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Photorealistic Rendering

Geometry

70's, 80's: Splines
90's: Range Data

Rendering Algorithm

Arnold Renderer: Marcos Fajardo

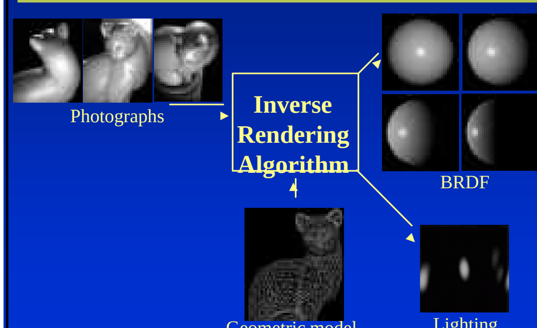
80's,90's: Physically based

Materials/Lighting

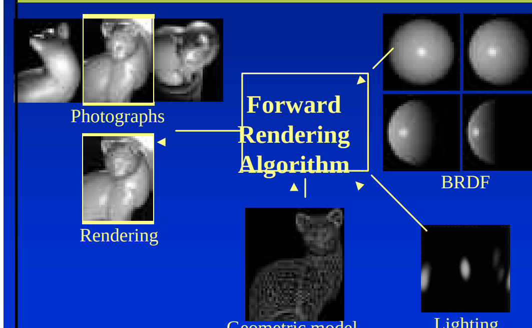
(Texture Reflectance[BRDF] Lighting)

Realistic input models required

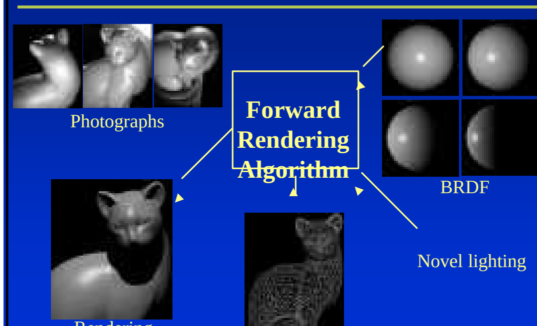
Flowchart



Flowchart



Flowchart



Assumptions

- Known geometry
- Distant illumination
- Homogenous isotropic materials
- Convex curved surfaces: no shadows, interreflection

Later, practical algorithms: relax some assumptions

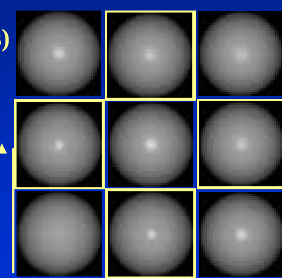
Inverse Rendering

	Lighting: Known	Lighting: Unknown
BRDF: Known		Miller and Hoffman 84 Marschner and Greenberg 97
BRDF: Unknown	Sato et al. 97 Dana et al. 99 Debevec et al. 00 Marschner et al. 00	Sato et al. 99 Nishino et al. 01

Textures are a third axis

Inverse Problems: Difficulties

Ill-posed
(ambiguous)



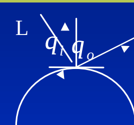
Surface roughness

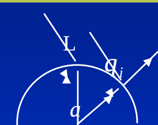
Angular width of Light Source

Contributions

1. Formalize reflection as convolution
2. Signal-processing framework
3. Analyze well-posedness of inverse problems
4. Practical algorithms

Reflection as Convolution (2D)





$$B(q_o) = \int_{-p/2}^{p/2} L(q_i)\, r(q_i, q_o)\, dq_i$$

Reflected Light Field — Lighting — BRDF

$$B(a, q_o) = \int_{-p/2}^{p/2} L(a + q_i)\, r(q_i, q_o)\, dq_i$$

Reflection as Convolution (2D)

$$B(a, q_o) = \int_{-p/2}^{p/2} L(a + q_i)\, r(q_i, q_o)\, dq_i$$

$$B = L \otimes r$$

Spatial: integral

Fourier analysis

$$B_{l,p} = 2p\, L_l\, r_{l,p}$$

Frequency: product

Spherical Harmonic Analysis

2D:

$$B(a, q_o) = \int_{-p/2}^{p/2} L(a + q_i)\quad r(q_i, q_o)\quad dq_i$$

$$B_{l,p} = 2p\, L_l\, r_{l,p}$$

3D:

$$B(a, b, q_o, j_o) = \int_0^{\frac{p}{2}} \int_0^{2p} L(R_{a,b}[q_i, j_i])\, r(q_i, j_i, q_o, j_o)\, dq_i\, dj_i$$

$$B_{lm,pq} = \Lambda_l\, L_{lm}\, r_{lq,pq}$$

Insights: Signal Processing

Signal processing framework for reflection
- Light is the signal
- BRDF is the filter
- Reflection on a curved surface is convolution

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Filter is Delta function : Output = Signal

Mirror BRDF : Image = Lighting

[Miller and Hoffman 84]

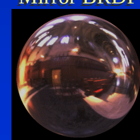

Image courtesy Paul Debevec

Insights: Signal Processing

Signal processing framework for reflection
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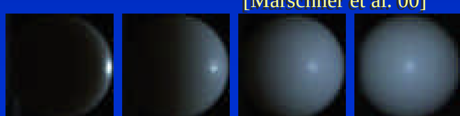
- BRDF is the filter
- Reflection on a curved surface is convolution

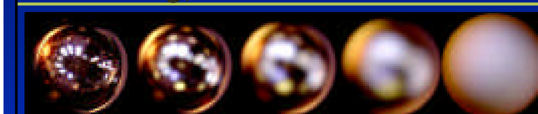
Signal is Delta function : Output = Filter

Point Light Source : Images = BRDF

[Marschner et al. 00]



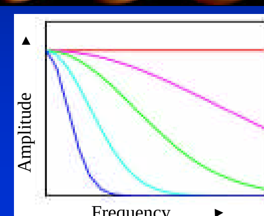
Phong, Microfacet Models



Mirror

Roughness

Illumination estimation
ill-posed for rough surfaces



Inverse Lighting

Given: B,? find L

$$B = L \otimes r$$

$$B_{lm,pq} = \Lambda_l L_{lm} r_{lq,pq}$$

$$L_{lm} = \frac{1}{\Lambda_l} \frac{B_{lm,pq}}{r_{lq,pq}}$$

Well-posed unless denominator vanishes
- BRDF should contain high frequencies : Sharp highlights
- Diffuse reflectors low pass filters: Inverse lighting ill-posed

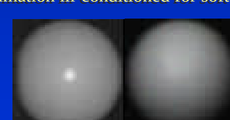
Inverse BRDF

Given: B,L find ?

$$r_{lq,pq} = \frac{1}{\Lambda_l} \frac{B_{lm,pq}}{L_{lm}}$$

Well-posed unless L_{lm} vanishes
- Lighting should have sharp features (point sources, edges)
- BRDF estimation ill-conditioned for soft lighting

Directional Source



Area source Same BRDF

Factoring the Light Field

Given: B find L and ?

$$\underset{4D}{B} = \underset{2D}{L} \otimes \underset{3D}{r}$$

More knowns (4D) than unknowns (2D/3D)

Light Field can be factored

- Up to global scale factor
- Assumes reciprocity of BRDF
- Can be ill-conditioned
- Analytic formula in paper

Practical Issues

- Incomplete sparse data (few photographs)
  Difficult to compute frequency spectra
- Concavities: Self Shadowing and Interreflection
- Spatially varying BRDFs: Textures

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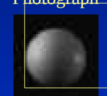
- Incomplete sparse data (few photographs)
  Difficult to compute frequency spectra
- Concavities: Self Shadowing and Interreflection
- Spatially varying BRDFs: Textures

Issues can be addressed; can derive practical algorithms
  Dual spatial (angular) and frequency-space representation
  Simple extensions for shadowing, textures

Algorithm Validation

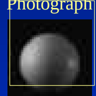
Photograph



	"True" values
K_d	0.91
K_s	0.09
μ	1.85
σ	0.13

Algorithm Validation

Photograph



Renderings

Known lighting   Unknown lighting

Image RMS error 5%

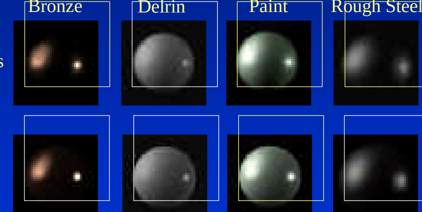
	"True" values	Known lighting	Unknown lighting
K_d	0.91	0.89	0.87
K_s	0.09	0.11	0.13
μ	1.85	1.78	1.48
σ	0.13	0.12	.14

Inverse BRDF: Spheres

Bronze   Delrin   Paint   Rough Steel

Photographs

Renderings (Recovered BRDF)



Complex Geometry

3 photographs of a sculpture
• Complex unknown illumination
• Geometry known
• Estimate microfacet BRDF *and* distant lighting

Comparison

Photograph Rendering

New View, Lighting

Photograph Rendering

Textured Objects

Photograph Rendering

Summary

- Reflection as convolution
- Signal-processing framework
- Formal study of inverse rendering
- Practical algorithms

Implications and Future Work

- Frequency space analysis of reflection
- Well-posedness of inverse problems
  - Perception, human vision
  - Forward rendering [Friday]
- Complex uncontrolled illumination

Acknowledgements

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Paper Website:
http://graphics.stanford.edu/papers/invrend

The End

The End

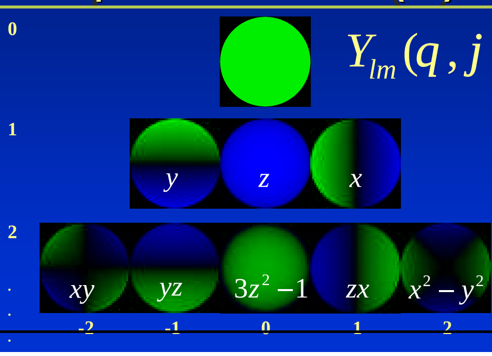
Related Work

- Qualitative observation of reflection as convolution: Miller & Hoffman 84, Greene 86, Cabral et al. 87,99
- Reflection as frequency-space operator: D’Zmura 91
- Lambertian reflection is convolution: Basri Jacobs 01

Our Contributions
- Explicitly derive frequency-space convolution formula
- Formal Quantitative Analysis in General 3D Case

Spherical Harmonics (3D)

$$Y_{lm}(\theta,\varphi)$$

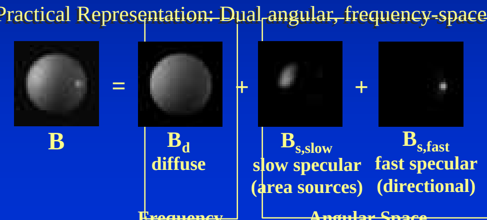


Dual Representation

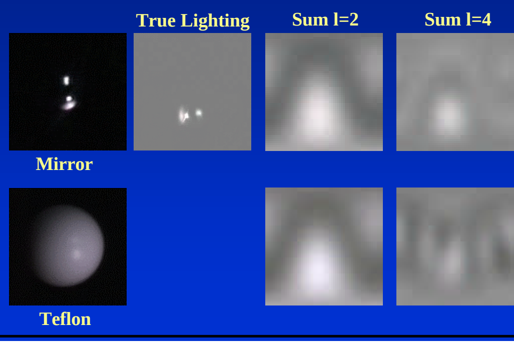
Diffuse BRDF: Filter width small in frequency domain

Specular: Filter width small in spatial (angular) domain

Practical Representation: Dual angular, frequency-space



Inverse Lambertian



Other Papers

- Linked to from website for this paper
  - http://graphics.stanford.edu/papers/invrend/
- Theory
  - Flatland or 2D using Fourier analysis [SPIE 01]
  - Lambertian: radiance from irradiance [JOSA 01]
- Application to other areas
  - Forward Rendering (Friday) [SIGGRAPH 01]
  - Lighting variability object recognition [CVPR 01]